Exceptional Control Flow: System Calls, Page Faults etc.

Slides adapted from: Gregory Kesden and Markus Püschel of Carnegie Mellon University

Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow

Time

<startup>
inst$_1$
inst$_2$
inst$_3$
…
inst$_n$
<shutdown>

Altering the Control Flow

- **Up to now: two mechanisms for changing control flow:**
  - Jumps and branches
  - Call and return

  React to changes in ***program state***

- **Insufficient for a useful system:**
  Difficult to react to changes in *system state*
  - Data arrives from a disk or a network adapter
  - Instruction divides by zero
  - User hits Ctrl-C at the keyboard
  - System timer expires

- **System needs mechanisms for "exceptional control flow"**

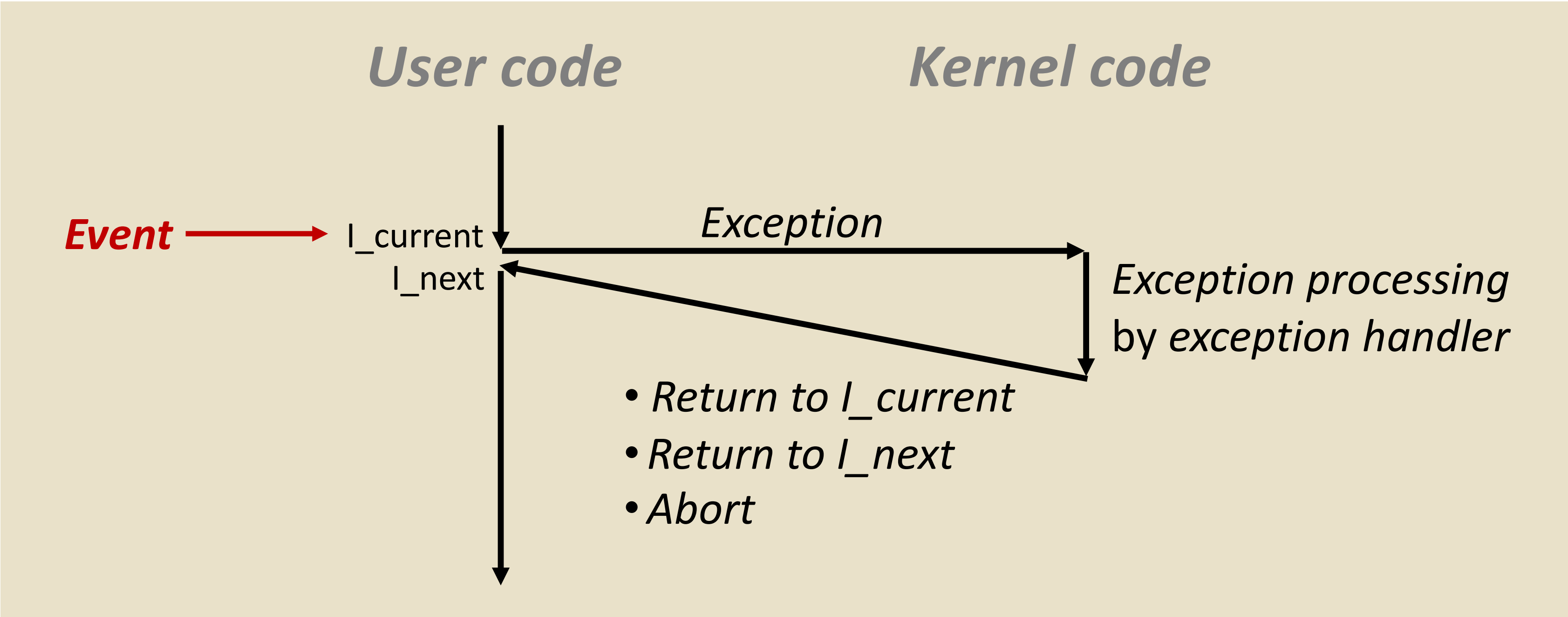
Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
  - 1. **Exceptions**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software

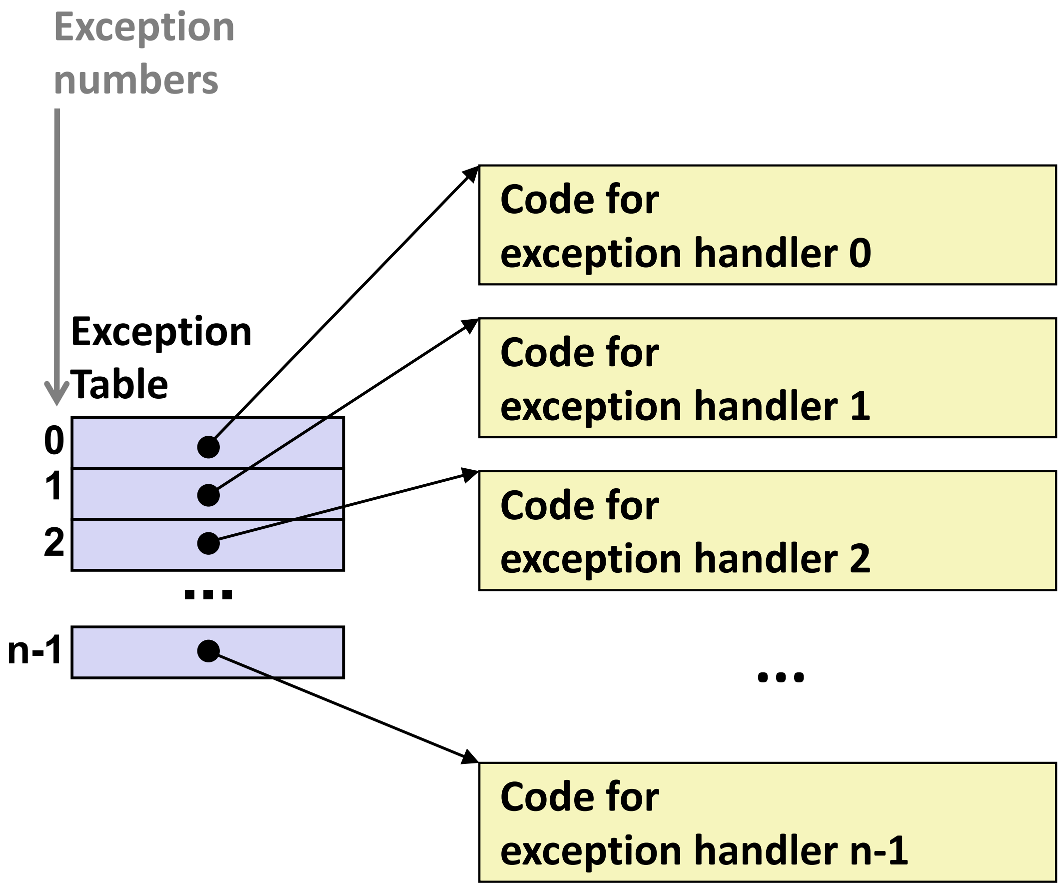
- **Higher level mechanisms**
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software
  - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - Implemented by C runtime library

Exceptions

- **An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)**
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C

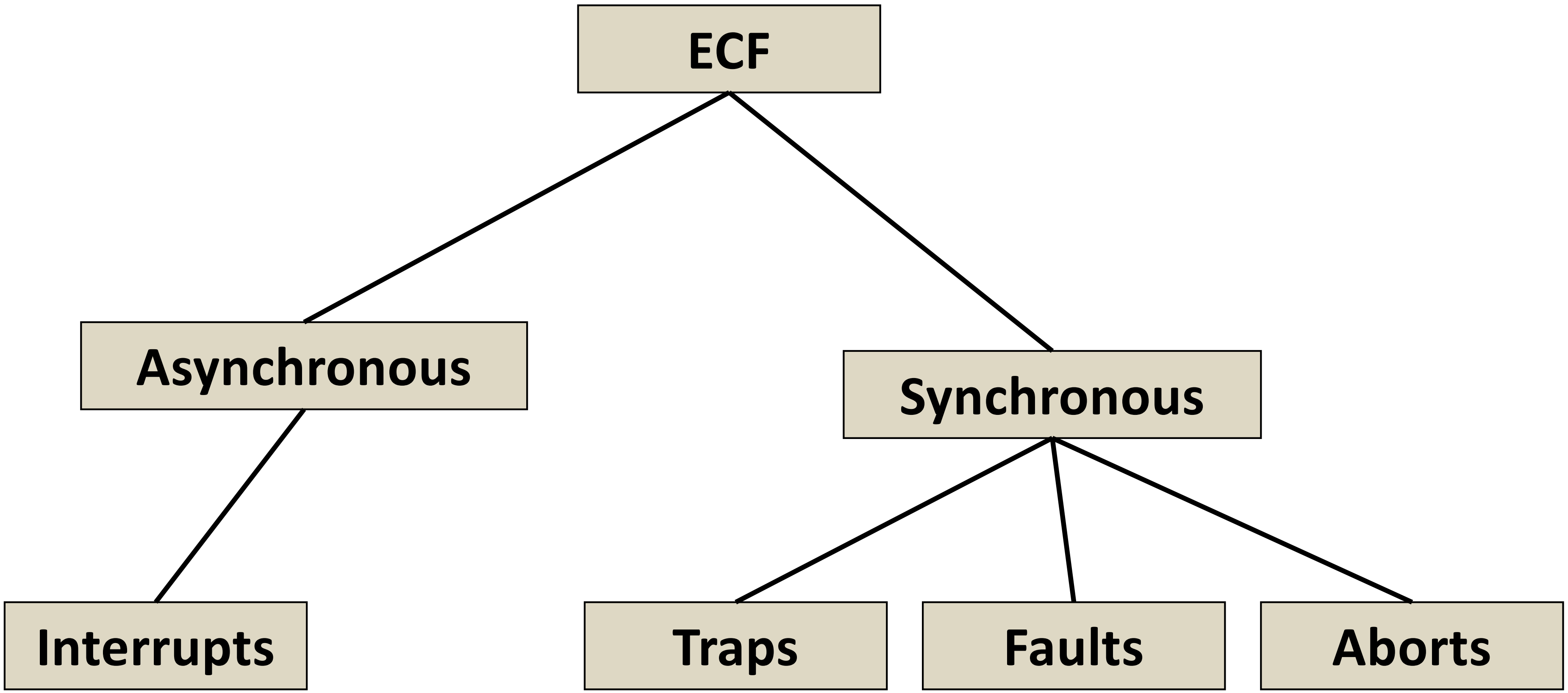


Exception Tables (also known as Interrupt Vector)



- Each type of event has a unique exception number k
- k = index into exception table (a.k.a. interrupt vector)
- Handler k is called each time exception k occurs

(partial) Taxonomy



Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor's *interrupt pin*
  - Handler returns to "next" instruction

- **Examples:**
  - Timer interrupt
    - Every few ms, an external timer chip triggers an interrupt
    - Used by the kernel to take back control from user programs
  - I/O interrupt from external device
    - Hitting Ctrl-C at the keyboard
    - Arrival of a packet from a network
    - Arrival of data from a disk

Synchronous Exceptions

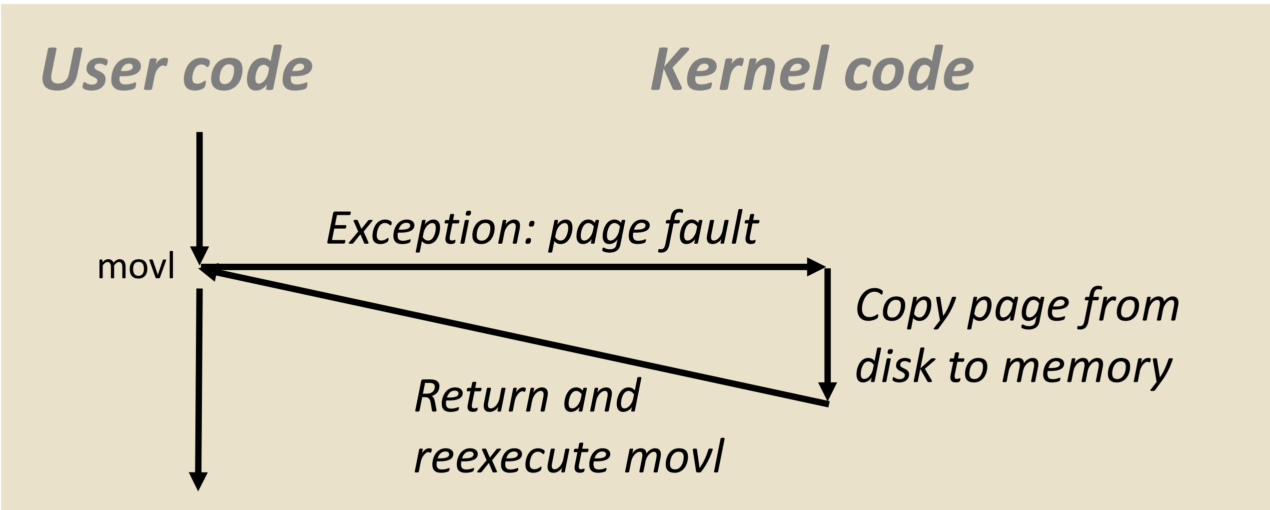
- **Caused by events that occur as a result of executing an instruction:**
  - ***Traps***
    - Intentional
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - Unintentional and unrecoverable
    - Examples: illegal instruction, parity error, machine check
    - Aborts current program

Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

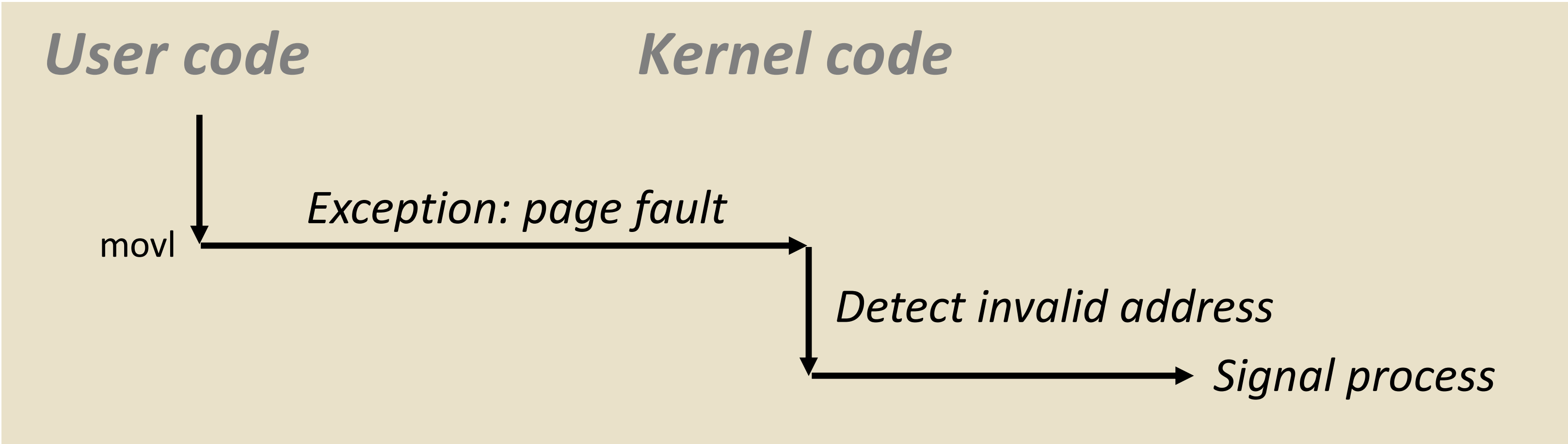
```
80483b7:        c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```



Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
80483b7:       c7 05 60 e3 04 08 0d   movl   $0xd,0x804e360
```



- Sends **`SIGSEGV`** signal to user process
- User process exits with "segmentation fault"

Traps: System Calls

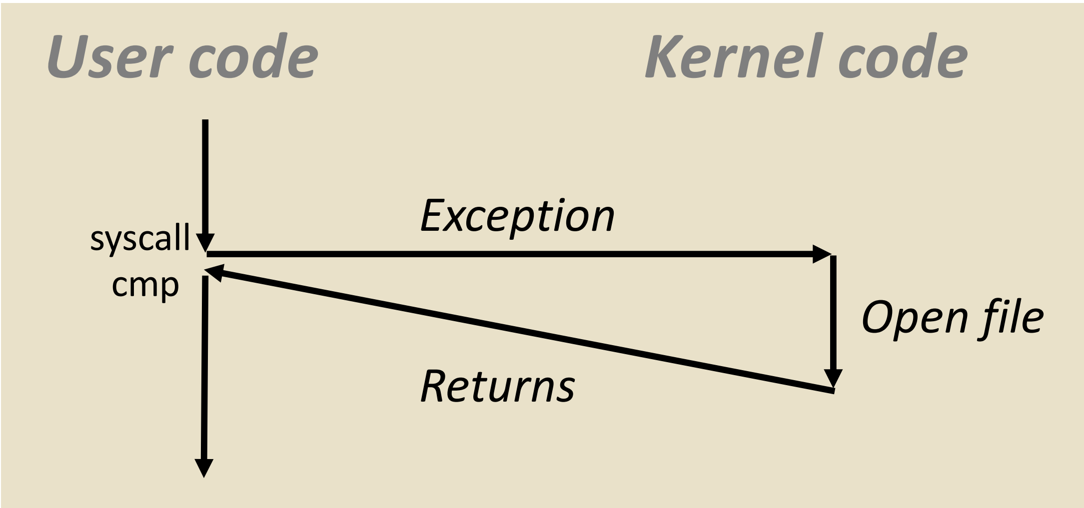
- **Each x86-64 system call has a unique ID number**
- **Examples:**

Number	*Name*	*Description*
0	`read`	Read file
1	`write`	Write file
2	`open`	Open file
3	`close`	Close file
4	`stat`	Get info about file
57	`fork`	Create process
59	`execve`	Execute a program
60	`_exit`	Terminate process
62	`kill`	Send signal to process

System Call Example: Opening File

- User calls: **`open(filename, options)`**
- Calls **`__open`** function, which invokes system call instruction **`syscall`**

```
00000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%eax  # open is syscall #2
e5d7e:   0f 05               syscall         # Return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

System call

- **Applications should be prevented to directly access hardware such as**
  - Physical memory,
  - disk,
  - network,
  - halt
- **But nevertheless, they need to access these resources in a controlled way:**
  - Read/write their own memory
  - Access the files that they have permission
  - Access the network for its own communications
  - Halt
- **Processors run at different security levels:**
  - User level:
  - Kernel-level:

Privileged instructions

- At kernel level, CPU can execute certain instructions (such as halt) that directly access hardware.
- At user-level the use of privileged instructions are not allowed by hardware.
- User applications do not include privileged instructions.
- Only System Call code includes privileged instructions.

System calls

- **Programming interface to the services provided by the OS**
  - A set of functions ("API" (Application Programming Interface)) provided by the OS to the user applications
  - Allow the user applications to access hardware in a controlled way
- **System calls are functions that can directly access hardware**

Library example

System Calls

- Process Control
  - Load, execute and, abort
  - create and terminate process
- File management
  - create file, delete file
  - open, close, read, write, seek
- Device Management
  - request device, release device
  - read, write, reposition
- Information Maintenance
  - get/set time or date, get/set system data
- Communication
  - create, delete communication connection
  - send, receive messages

Most common System API

- **Most common system API**
  - **POSIX** API (most versions of UNIX, Linux, and Mac OS X)
  - **Win32** API for Windows
- On Unix, Unix-like and other POSIX-compliant operating systems, popular system calls are **`open`**, **`read`**, **`write`**, **`close`**, **`wait`**, **`exec`**, **`fork`**, **`exit`**, and **`kill`**

Most common System API

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  - **POSIX** API (most versions of UNIX, Linux, and Mac OS X)
  - **Win32** API for Windows
- **POSIX (IEEE 1003.1, ISO/IEC 9945)**
  - Very widely used standard based on (and including) C-language
  - Defines both
    - ***system calls*** and
    - compulsory ***system programs*** together with their functionality and command-line format
      - E.g. `ls -w dir` prints the list of files in a directory in a 'wide' format
  - Complete specification is at http://www.opengroup.org/onlinepubs/9699919799/nframe.html
- **Win32 (Microsoft Windows based systems)**
  - Specifies system calls together with many Windows GUI routines
    - VERY complex, no really complete specification

System programs

- **System programs are "utilities" that are commonly bundled with the Operating System, to facilitate its use by the user.**
  - File Management
    - `rm`
  - Status information
    - `ps`
  - File modification
    - `vi`
  - Programming Language support
    - `gcc`
  - Program loading and execution
    - `ld`
  - Communication
    - ssh
- **There is nothing special about a system program. They are merely user applications, and you can replicate them.**
  - E.g. you can write your own "`ls`"
- **Don't ever confuse them with system calls!**